NACA

RESEARCH MEMORANDUM

EFFECT OF ENGINE SKEW ON DIRECTIONAL AND LATERAL

CONTROL CHARACTERISTICS OF SINGLE-ENGINE AIRPLANES

By

Arthur R. Wallace and Raymond J. Comenzo

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
May 16, 1947

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF ENGINE SKEW ON DIRECTIONAL AND LATERAL CONTROL CHARACTERISTICS OF SINGLE-ENGINE AIRPLANES

By Arthur R. Wallace and Raymond J. Comenzo

SUMMARY

An investigation has been conducted and an analysis made on the effect of engine skew on the directional and lateral control characteristics of a single-engine airplane with a single-rotating propeller. The investigation consisted of tests in the Langley 7- by 10-foot tunnel of a $\frac{1}{5}$-scale model of a single-engine airplane with a skewed thrust axis. With the aid of wind-tunnel data, estimations were made of the effect of skewed thrust axis on the full-scale airplane and these were compared with flight tests of an F6F-3 airplane with a skewed thrust axis and offset fin.

The estimated and flight test results considered herein showed quite definitely the advantages to be gained by a skewed position of a single-rotating propeller of a single-engine airplane. The data indicated that the skewed thrust axis is an effective method of overcoming inadequate rudder control in power-on flight at low speeds and that it also had a pronounced effect on aileron control, particularly with flaps deflected. There were indications that the vertical tail loads obtained and rudder pedal forces required in a high-speed dive would be less than with the normal thrust axis.

INTRODUCTION

Conventional single-engine airplanes with single-rotating propellers usually require large changes in rudder angle for trim with power on through the speed range and also with power changes at a constant speed. During take-off, asymmetric yawing moments due to the propeller slipstream are so severe on some airplanes that full rudder is insufficient to allow take-off in a straight path. Although the pilot learns to coordinate rudder pedal movements with throttle movements, the situation is still objectionable because the control available for maneuvering is greatly reduced.

Attempts have been made to increase the amount of rudder control available by increasing the rudder chord of offsetting the fin but these are disadvantageous because of large pedal forces which may result. One method used to reduce the adverse effects of asymmetric yawing and rolling moments is to shift the center of gravity to the right relative to the thrust axis, for right-hand propellers. This method has been found effective when tested. (See reference 1.)

Another method which has been proposed is to skew the thrust axis through a small angle so as to produce a thrust moment which counteracts the normal asymmetric yawing moment. Engine torque reaction is known to be troublesome in at least one type of airplane, namely, the single float seaplane. During take-off one wing tip remains in the water long after desired. This is due to the inability of the ailerons to neutralize engine torque reaction until near take-off speed. Skewing the thrust axis also produces favorable rolling moments by directing more of the slipstream over one wing half than the other.

The purpose of the present paper is to investigate briefly the effects of skewing the thrust axis. A concise theoretical analysis and flying quality estimations obtained from data of tests of a $\frac{1}{5}$-scale model of the XF2M-1 airplane with normal and skewed thrust axis in the Langley 7- by 10-foot tunnel are presented. Data acquired from flight tests made by the Grumman Aircraft Corporation of an F6F-3 airplane with normal and skewed thrust axis and offset fin are also presented.

COEFFICIENTS AND SYMBOLS

The positive directions of the stability axes of angular displacements of the airplane and control surfaces, and of hinge moments are shown in figure 1. The following coefficients and symbols appear in the text and figures:

C_Y lateral-force coefficient (Y/qS)

C_l rolling-moment coefficient (L/qSb)

C_n yawing-moment coefficient (N/qSb)

C_h hinge-moment coefficient $(H/qb\bar{c}^2)$

T_c' effective thrust coefficient based on wing area (T_{eff}/qS)

C_T effective thrust coefficient $(T_{eff}/\rho n^2D^4)$

T_c effective thrust coefficient $(T_{eff}/\rho V^2D^2)$

C_Q torque coefficient $(Q/\rho n^2D^5)$

Q_c' torque coefficient based on wing area and span (Q/qSb)

Q_c torque coefficient $(Q/\rho V^2D^3)$

T_{eff} propeller effective thrust, pounds

Q propeller torque, pound-feet

η propulsive efficiency $(T_{eff}V/2\pi nQ)$

Y force along Y-axis, pounds

$\left.\begin{matrix} L \\ N \end{matrix}\right\}$ moments about axes, pound-feet

H hinge moment of control surface, pound-feet

q free-stream dynamic pressure, pounds per square foot $\left(\frac{\rho V^2}{2}\right)$.

S wing area (9.40 sq ft on model)

c airfoil section chord, feet

$\bar{c}$ root-mean-square chord of a control surface back of hinge line, feet

b wing span (7.51 ft on model)

b' control-surface span along hinge line, feet

V air velocity, feet per second

V_i indicated airspeed (mph)

D propeller diameter (2.27 ft on model)

n propeller speed, revolutions per second

F stick force, pounds

a distance from propeller center line to center of gravity (18.32 in. on model)

d distance between skewed thrust line and center of gravity (1.59 in. on model)

h vertical displacement of center-of-gravity from thrust line (1.14 in. on model)

ρ mass density of air, slugs per cubic foot

α angle of attack of thrust line, degrees

ψ angle of yaw, degrees

γ angle of skew, degrees

δ control-surface deflection, degrees

Subscripts:

a aileron (a_R, a_L, right and left aileron)

r rudder

f flap

p propeller

ψ denotes partial derivatives of a coefficient with respect to yaw

Example: $C_{l_\psi} = \frac{\partial C_l}{\partial \psi}$.

MODEL AND AIRPLANE TESTED

Model

The model which was tested in the Langley 7- by 10-foot tunnel to provide data for estimating the flying qualities presented herein is a $\frac{1}{5}$-scale model of the General Motors XF2M-1 airplane, a conventional single-engine fighter. (See fig. 2.) Thrust coefficients for the model were such that the full-scale power represented was 1500 brake horsepower with a wing loading W/S of 31.25 pounds per square foot. The model propeller was to scale diameter, but the propeller blade chord was not to scale. However, full-scale value of T_c'/Q_c' was obtained by interpolation between tests at two model propeller blade angles. The full-scale propeller for which the flying quality estimations were made was a three-blade Hamilton Standard design No. 6259A-18 with NACA 16-series blade sections. Figure 3 shows the estimated power characteristics of the XF2M-1 airplane using propeller data obtained from reference 2.

For the skewed-thrust-axis tests the engine shaft was skewed about the intersection of the propeller plane with the airplane center line as shown in figure 4.

The brake horsepower simulated for various wing loadings and model scales by the test variation of T_c' against C_L is presented in figure 5.

Airplane

The F6F-3 airplane (fig. 6) was tested by the Grumman Aircraft Corporation with fin at 0° and offset -2° with normal thrust axis and with the thrust axis skewed 2° with 0° fin setting. The airplane engine was skewed about the center of the engine mount. The F6F-3 was tested with rated power (1650 bhp at 2550 rpm propeller speed), 1/2 rated power, and with windmilling propeller.

TEST PROCEDURE

For the skewed and unskewed thrust axis conditions, tests of the model through the angle-of-attack range with power on and zero angle of yaw with several rudder deflections were run to procure the effect of skewed thrust axis on rudder angle required for trim through the flight range. A sample figure showing the form in which the above tests were plotted is given as figure 7.

In order to obtain the effect of skewed thrust axis during ground run, tests were run with the model set at zero angle of attack and zero angle of yaw, and the components plotted on figure 8 were read for a range of propeller speeds. These tests were also used to obtain the effect of skewed thrust axis on aileron angle required. For computations down to zero speed in take-off, plots of N, Y, L, and H_R against T_{eff} are required. (See sample plot fig. 9.)

THEORY

The asymmetric yawing moment encountered in the power-on condition with the normal thrust axis is due principally to the vertical tail surface operating at an effective angle of attack other than zero, when the airplane is at zero sideslip. This change in effective angle of attack at the tail is a function of the rotational velocity in the slipstream (which in turn is a function of the torque coefficient), the relative geometry of the slipstream and the tail, and the axial velocity at the tail. Other contributing factors are the effect of the slipstream on the wing fuselage interference and the yawing moment produced by the propeller in pitch. This asymmetric yawing moment, which is negative for a right-hand propeller, has to be trimmed before a straight flight path can be maintained.

Skewing the thrust axis has the following actions which are beneficial for the reduction of rudder deflection necessary for trim:

A yawing moment is produced by the thrust acting at a distance from the center of gravity, as shown in figure 4, which counteracts the yawing moment produced by the slipstream rotation. The yawing-moment coefficient increases with thrust coefficient and, therefore, is greatest at low speeds, as can be seen with the aid of figure 3. The skew of the thrust axis gives rise to an incremental side force in the plane of the propeller (fin effect). There is a corresponding incremental sidewash at the vertical tail in the opposite direction. Both effects add yawing moments that augment the direct thrust moment caused by the skew.

Engine torque reaction causing the left wing to be depressed for right-hand propeller is the main difficulty encountered in aileron control during take off. This torque reaction is slightly annoying for landplanes but is more bothersome for single float seaplanes, below take-off speed. At high speeds the engine torque reaction is not particularly bothersome. The skewed thrust axis directs the slipstream more over one half of the wing than the other, from which results an asymmetrical lift due to power counteracting the engine torque reaction. The skewed thrust axis is more effective flaps down because the lift increment due to the slipstream over the wing is greater; it is also more effective at the high thrust coefficients associated with low speeds. (See fig. 3.)

METHOD OF ANALYSIS

Estimating Required Data in Absence of Wind-Tunnel Data

For the case with a normal thrust axis, the sidewash at the vertical tail can be estimated by the method of reference 3 from which asymmetric C_n, C_l, and C_Y can be computed from the vertical tail and propeller characteristics.

From data with a zero skew thrust axis estimations can be made for a skewed thrust axis in which four additional factors must be considered as follows:

1. Direct thrust of the propeller.

2. Side force on the propeller.

3. Change in sidewash at the tail.

4. The asymmetric lift created by the slipstream passing over one wing half more than the other.

The direct thrust of the propeller affects C_Y, C_n, and C_l in the following manner:

1. $C_Y = T_c' \sin \gamma$

2. $C_n = T_c' \, d/b$

3. $C_l = T_c' \sin \gamma \, h/b$

The difference in effective thrust coefficient between the unskewed and skewed thrust axis is believed to be negligible.

The side force of the propeller also affects these three components as follows:

1. $C_Y = C_{Y_p} \cos \gamma$

2. $C_n = C_{Y_p} a/b$

3. $C_l = C_{Y_p} \cos \gamma \; h/b$

where h is the vertical displacement of the center of gravity from the thrust line. An explanation of the other symbols is shown in figure 4. Generally, the angle of skew is small; therefore it can be assumed that $\sin \gamma = \frac{\gamma}{57.3}$ and $\cos \gamma = 1.0$. The side force of the propeller C_{Y_p} can be estimated with the aid of reference 4. The change in sidewash at the vertical tail can also be estimated with the aid of reference 4. Knowing the change in angle of attack of the vertical tail, the increments in C_Y, C_n, and C_l contributed by the vertical tail are readily computed, as for the zero skew condition. The asymmetric lift produced by the slipstream (rolling moment) can be estimated with the aid of reference 5 by first estimating the increment in lift on the wing and second estimating how far the slipstream is displaced laterally when it reaches the center of pressure of the wing.

The increments in C_Y, C_n, and C_l can now all be added to the zero skew condition to obtain the skewed condition and the results plotted in a similar way to the plots obtained for wind-tunnel tests.

Estimation of Flying Qualities from Skewed Thrust Axis Data

Free flight.- For this condition all forces and moments must be in trim. When C_n is reduced to zero by rudder deflection, C_Y is usually not quite zero, at zero sideslip. This small C_Y can be neutralized by banking the airplane so that a component of the weight is equal and opposite to C_Y; or if the wings are held level the airplane will sideslip slightly until C_Y equals zero. The latter condition represents the manner in which airplanes are flown and is the condition assumed in this report.

Rudder and sideslip angles for trim can be obtained by cross plotting C_n against δ_r. To obtain the correction due to sideslip the values of C_{n_ψ} and C_{Y_ψ} are required from estimates or wind-tunnel tests.

Once the rudder and sideslip angles are known the asymmetric C_l may easily be obtained from a cross plot of C_l against δ_r making a correction due to sideslip with the value of C_{l_ψ} acquired from estimates or wind-tunnel tests. The value of C_l is then located on a plot of C_l against total δ_a (obtained from wind-tunnel tests or estimates) to determine the total aileron deflection required for trim.

Particular caution is required with regard to signs since the control-surface deflection required to oppose the out-of-trim force or moment must be used instead of the control-surface deflection required to produce this out-of-trim force or moment.

Inclusion of ground reaction (landplane).- For the present report the airplane was assumed to be maintained in a level condition ($\alpha = 0$) for the entire ground run. Tail-wheel reaction was assumed zero and computations were made for only the conventional landing gear. A coefficient of rolling friction of 0.02 and zero sideslip were assumed. It was also assumed that no brakes were used to help correct asymmetric yawing moments.

Although no rudder deflection data were obtained for the flaps-deflected condition, the data for the flaps-up condition are believed to be applicable within reasonable accuracy since the presence of the ground prevents the slipstream from being greatly deflected downward by the flaps.

It was found that the free-flight rudder angles with wings level trim did not fair smoothly into the rudder angles with ground reaction at zero angle of sideslip. For this reason it is believed that a transition period occurs between 75 and 85 miles per hour in which the behavior of the airplane is dependent on the actual flight tests of the airplane in question and is indeterminable from wind-tunnel tests.

Inclusion of water reaction (single-float seaplane).- For the present report the seaplane was assumed to be at zero angle of bank and the aileron angles required to maintain the level condition were computed. The rudder angles on the seaplane are not given since they are substantially the same as for the landplane. The water reaction was assumed to produce no yawing moments since the single main float is directly below the center of gravity with wings level, which also means both wing tip floats would be out of the water.

Data were obtained for flaps neutral and deflected, in this instance, since flap deflection has a pronounced effect on the lift increment produced by the slipstream and hence the rolling moment, with a skewed thrust axis.

DISCUSSION

Effect of Offset Fin and Skew on Rudder Control

Estimated effect on XF2M-1 airplane.- The effect of skewed thrust axis on rudder control is presented in figure 10. Trimming the airplane at zero sideslip on the ground and calculating the effect of ground reaction, it is shown (fig. 10) that with the normal thrust axis the rudder control available is insufficient at low speeds, whereas with the skewed thrust axis the rudder deflection required is reduced considerably. Above cruising speeds the skewed thrust axis has a negligible effect on rudder effectiveness.

Effect on F6F-3 airplane.- In general, the results obtained from flight tests of the F6F-3 airplane have the same trend as those estimated for the XF2M-1 airplane. Data of figure 11 indicate the distinct advantage of the skewed thrust axis which is the reduction of rudder angle required for trim throughout the speed range, with power on. However, with windmilling propeller the effect of skewed thrust axis is negligible. Offsetting the fin has no effect on the variation of rudder angle required for trim with speed, although with power on the curve is displaced in such a manner that the rudder angle required for trim is reduced at low speeds. With windmilling propeller the offset fin has a detrimental effect on the rudder angle required for trim throughout the speed range.

Effect of Skewed Thrust Axis on Aileron Control

The data (fig. 12) indicate that the skewed thrust axis reduces the aileron deflection required for trim at low speeds and has a negligible effect at high speeds, with flaps up. It is believed that with flaps deflected the thrust axis was excessively skewed which resulted in reversal of aileron deflection required for trim of the same magnitude, at low speeds. A skewed thrust axis of approximately 3° would be a happy medium and would reduce the aileron deflection required for trim at low speeds. At high speeds the effect of skewed thrust axis is negligible, with flaps deflected.

Miscellaneous Effects of Skewed Thrust Axis

Stability and vibrations.- The skewed thrust axis is believed to have no adverse effects on longitudinal, lateral, or directional stabilities. However, it may cause the vertical tail to stall at a different angle of yaw, with power on.

Normally an airplane flies through large angles of yaw and pitch and no propeller vibration difficulty has been encountered; therefore, it is believed that no serious vibration problem will have to be overcome with a skewed thrust axis.

Performance.- With the thrust axis in the skewed position the propeller is at an angle of yaw when the airplane is at zero sideslip. In this particular case the angle of yaw is 5° and from figure 13, which was prepared from data of reference 6, it is shown that for 5° of yaw the propeller efficiency decreases about 1 percent. A 1 percent loss in efficiency causes a loss of 2.0 miles per hour at a speed of 400 miles per hour.

When operating at high speeds, the change in section blade angle of attack due to the skewed thrust axis causes a reduction in the critical tip speed of the propeller (reference 7); therefore compressibility effects will occur at a somewhat lower speed.

Vertical tail loads.- No data were obtained from which vertical tail loads can be calculated for the skewed thrust axis; therefore an attempt has been made to obtain an indication of the vertical tail loads. From figure 14 it is believed that the tail loads will probably be less with the skewed thrust axis than with the normal thrust axis.

Rudder pedal force in dive.- Calculations based on hinge moment data indicate (fig. 15) that the rudder forces required in a high-speed dive condition will probably be less with the skewed thrust axis than with the normal thrust axis.

CONCLUSIONS

From the estimated and experimental results obtained with the skewed thrust axis, the following conclusions can be drawn:

1. The rudder deflection required for trim was reduced considerably at low speeds with the skewed thrust axis.

2. Estimations made for a single-float seaplane revealed that the skewed thrust axis reduced the aileron deflection required for trim with flaps up. With flaps deflected the thrust axis was believed to be excessively skewed, thereby producing a reversal of aileron deflection required for trim of the same magnitude as that obtained for normal thrust axis.

3. The data indicated that the rudder forces required in a high-speed dive and the vertical tail loads obtained will probably be less with the skewed thrust axis than with the normal thrust axis.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

REFERENCES

1. Phillips, W. H., Crane, H. L., and Hunter, P. A.: Effect of Lateral Shift of Center of Gravity on Rudder Deflection Required for Trim. NACA RB No. L4I06, 1944.

2. Gray, W. H.: Wind-Tunnel Tests of Two Hamilton Standard Propellers Embodying Clark Y and NACA 16-Series Blade Sections. NACA MR, Aug. 20, 1941.

3. Purser, Paul E., and Spear, Margaret F.: Tests to Determine Effects of Slipstream Rotation on the Lateral Stability Characteristics of a Single-Engine Low-Wing Airplane Model. NACA TN No. 1146, 1946.

4. Ribner, Herbert S.: Notes on the Propeller and Slipstream in Relation to Stability. NACA ARR No. L4I12a, 1944.

5. Goett, Harry J., and Pass, H. R.: Effect of Propeller Operation on the Pitching Moments of Single-Engine Monoplanes. NACA ACR, May 1941.

6. Runckel, Jack F.: The Effect of Pitch on Force and Moment Characteristics of Full-Scale Propellers of Five Solidities. NACA ARR, June 1942.

7. Pendley, Robert E.: Effect of Propeller-Axis Angle of Attack on Thrust Distribution over the Propeller Disk in Relation to Wake-Survey Measurement of Thrust. NACA ARR No. L5J02b, 1945.

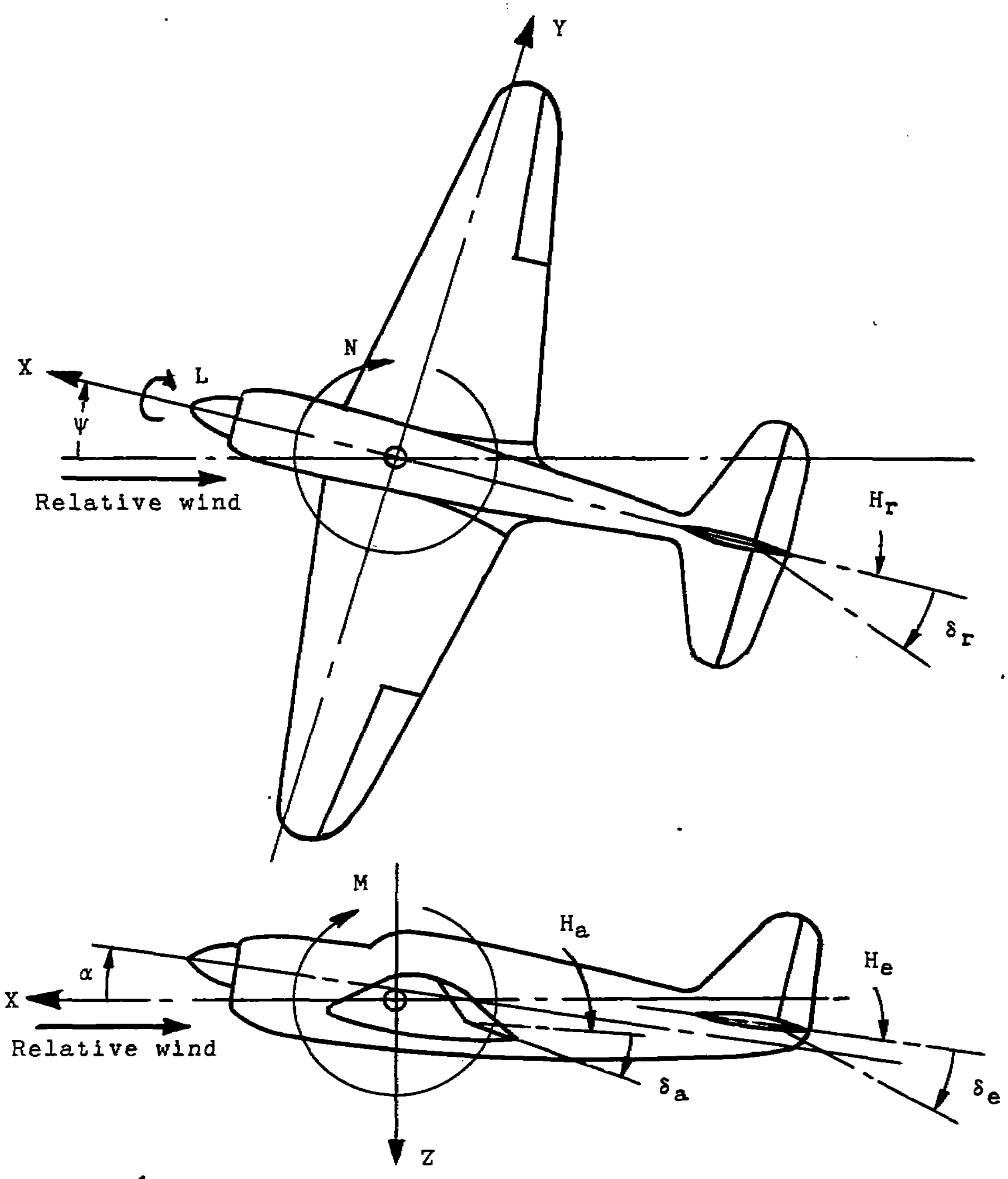


Figure 1 .- System of axes and control-surface hinge moments and deflections. Positive values of forces, moments, and angles are indicated by arrows. Positive values of tab hinge moments and deflections are in the same directions as the positive values for the control surfaces to which the tabs are attached.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

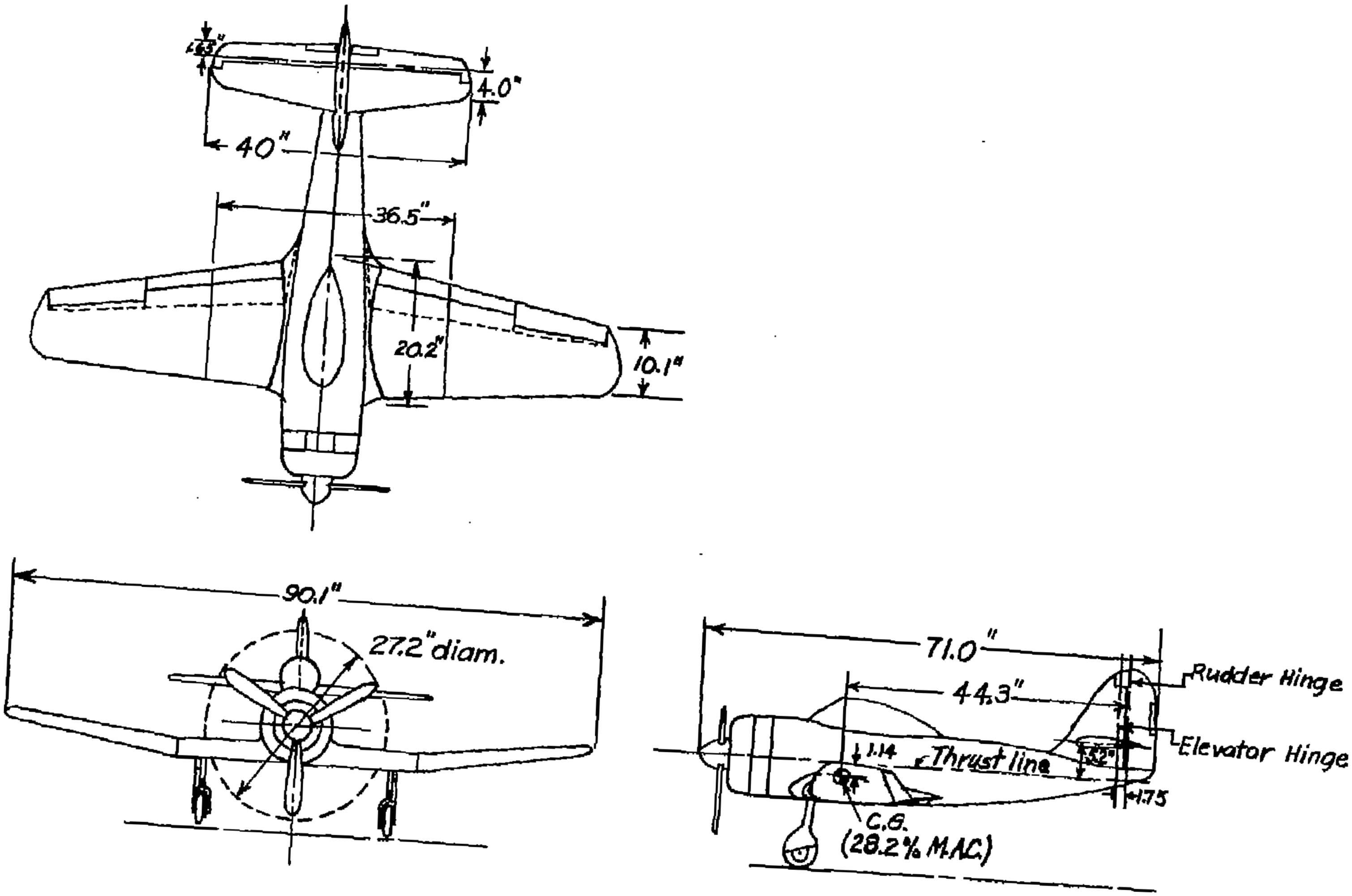


Figure 2.- Three-view of the 1/5-scale model of the XF2M-1 fighter airplane.

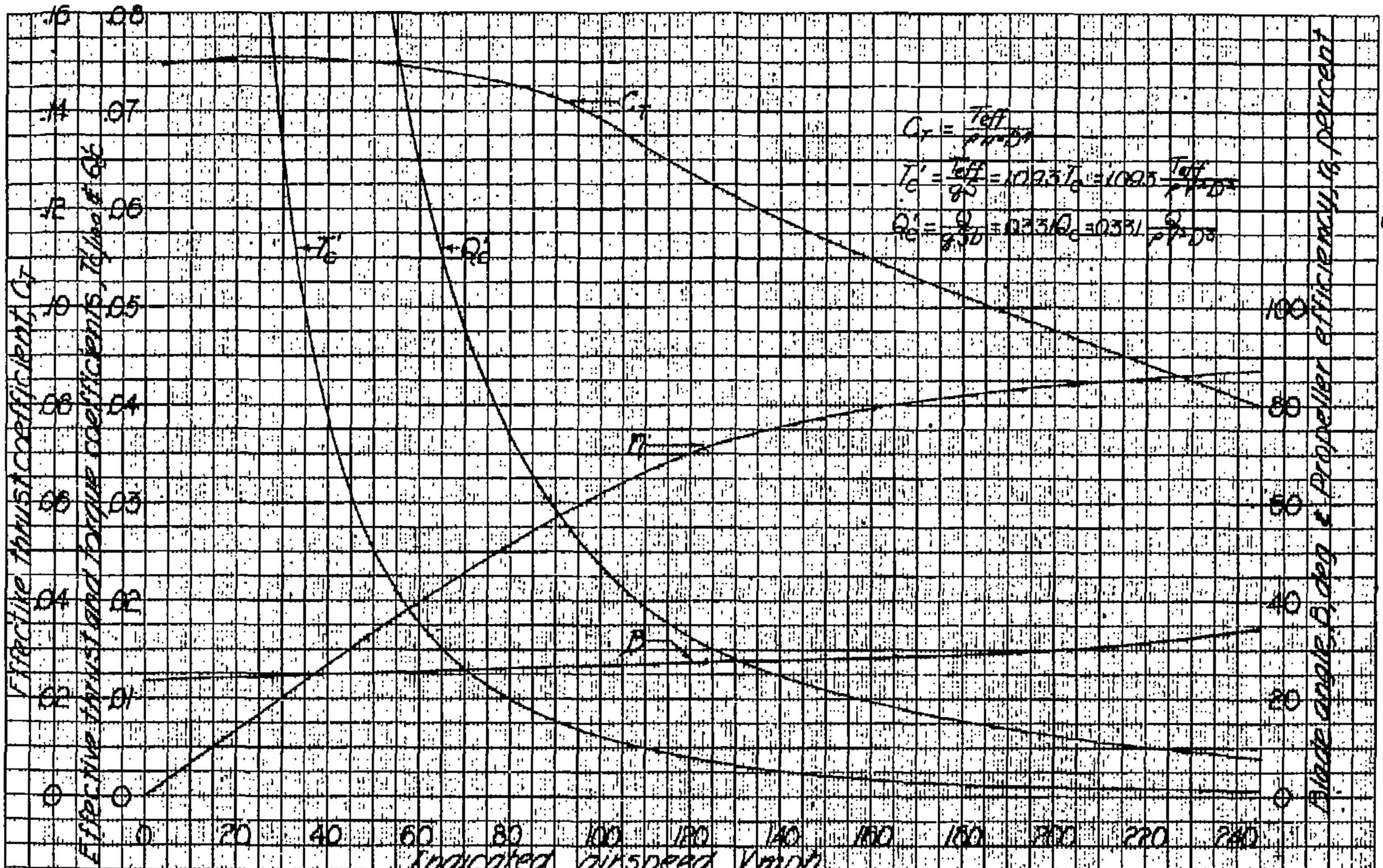


Figure 3. - Estimated characteristics for the XF2M-1 airplane obtained with a three-blade Hamilton Standard propeller with 16-series airfoil section (reference 2). 1500 bhp at sea level with a propeller speed of 1519 rpm. D, 11.35 ft; S, 235 sq ft; b, 37.5 ft; C_q, 0.0183.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

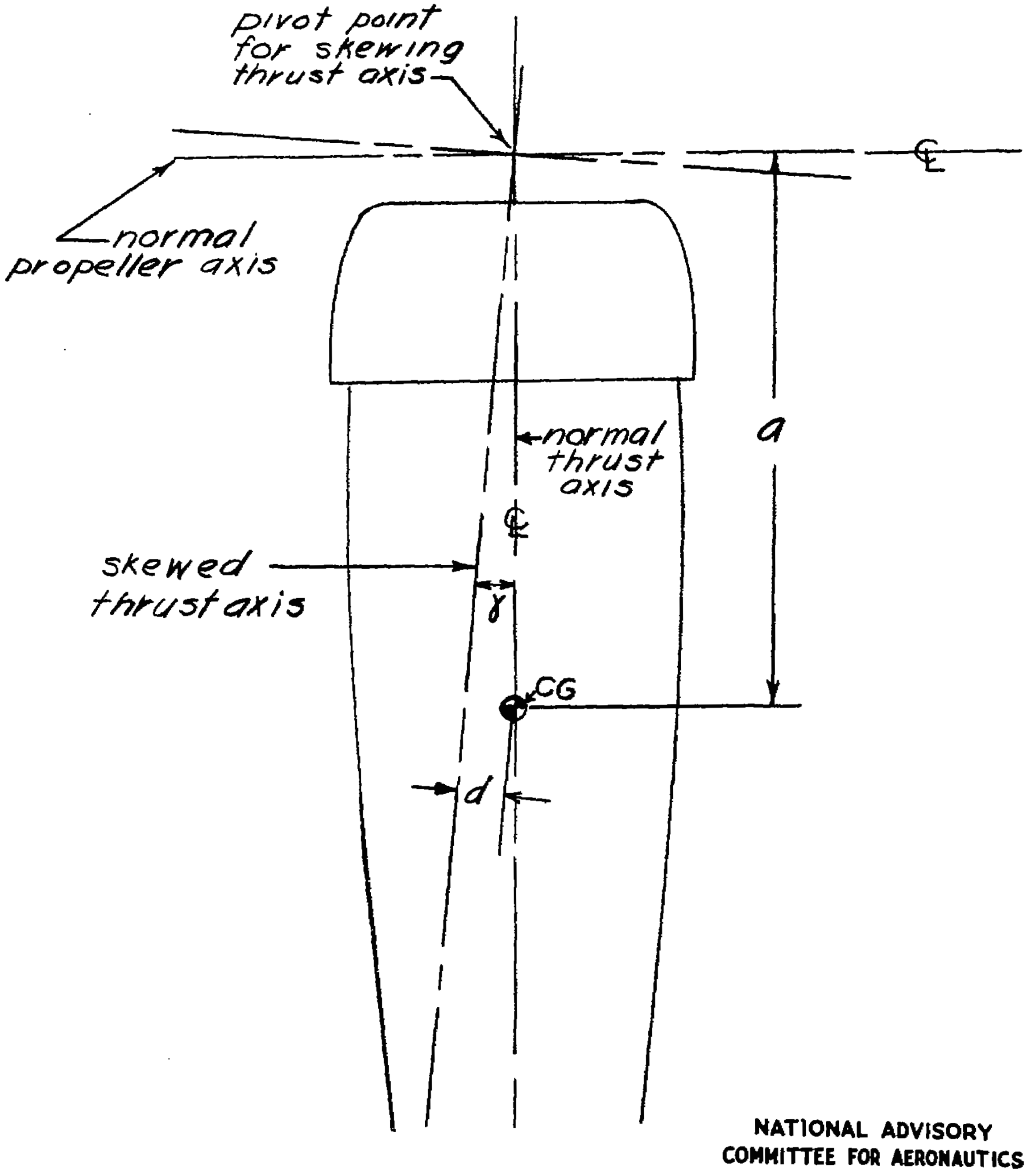


Figure 4.- Diagram showing how the thrust axis was skewed. Vertical position of thrust axis remained fixed.

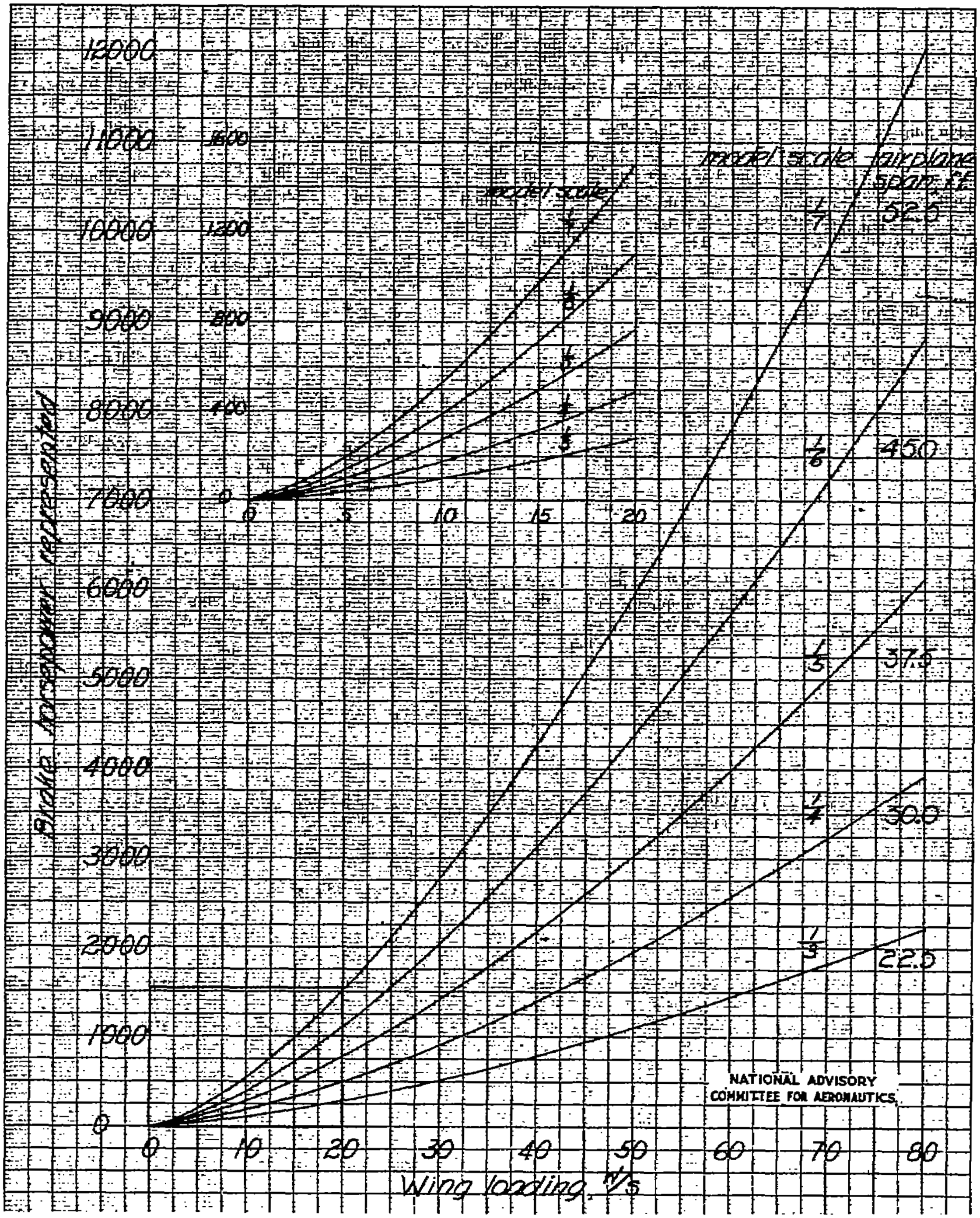
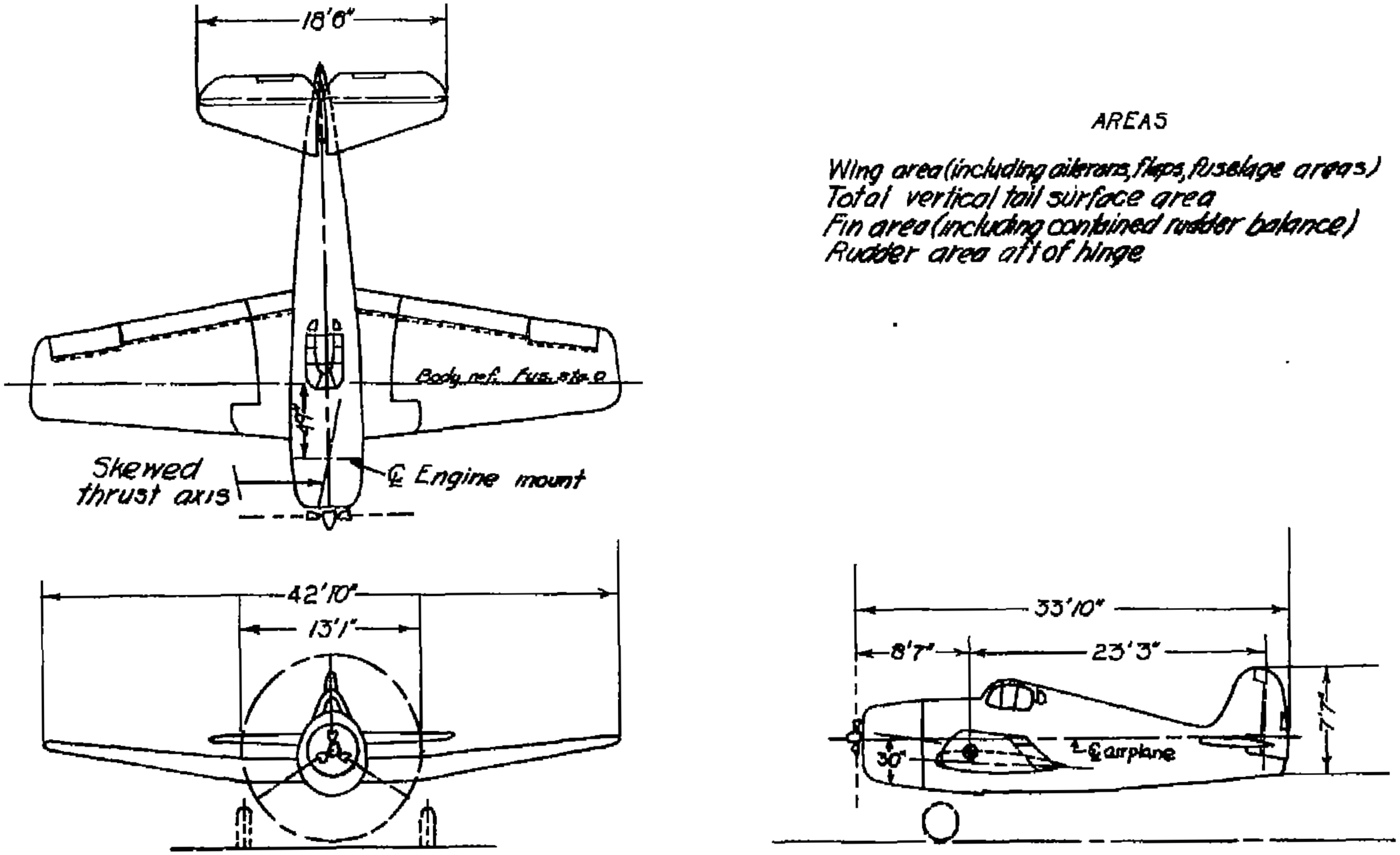
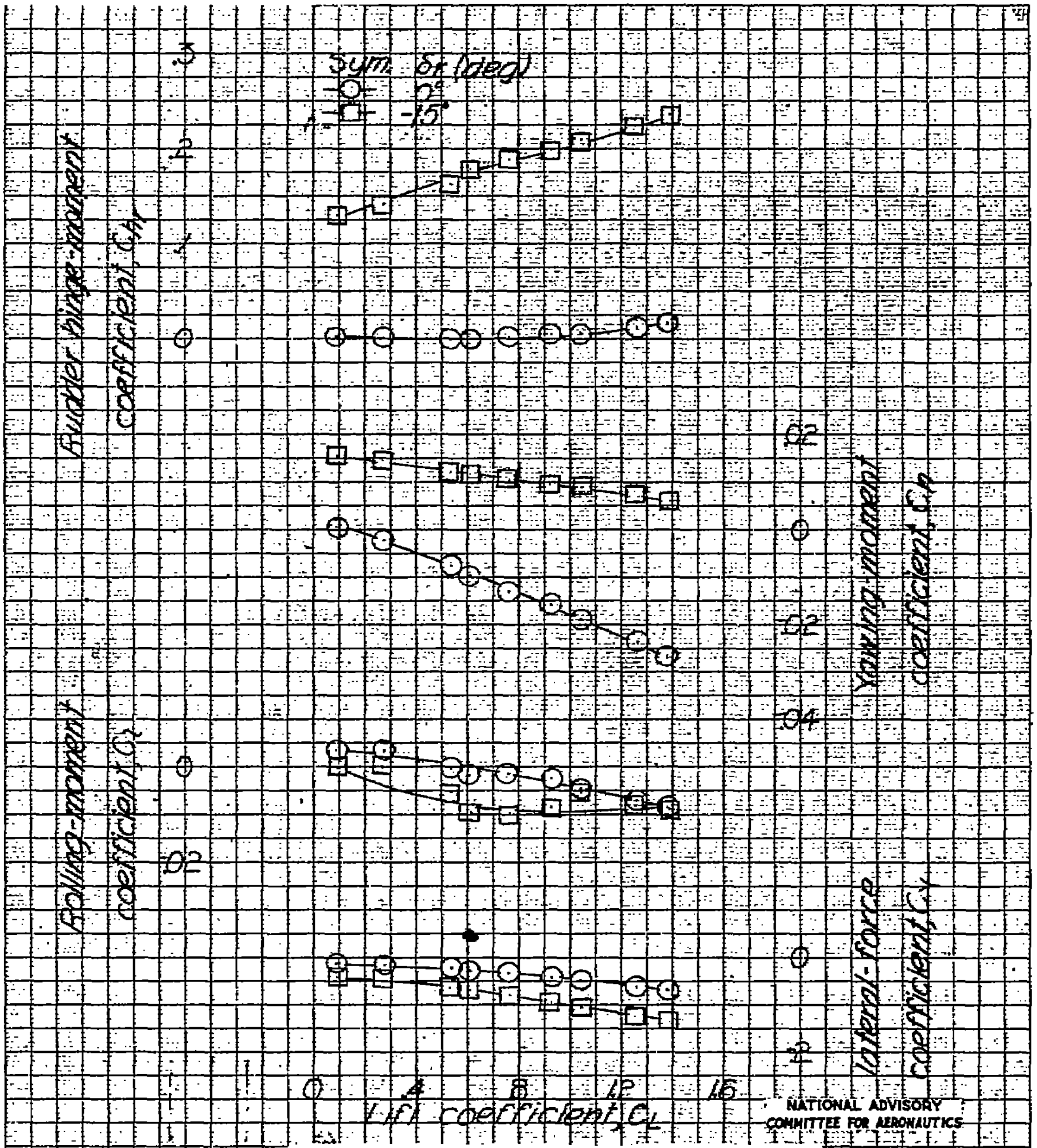


Figure 5.- Brake horsepower represented for various wing loadings and model scales.



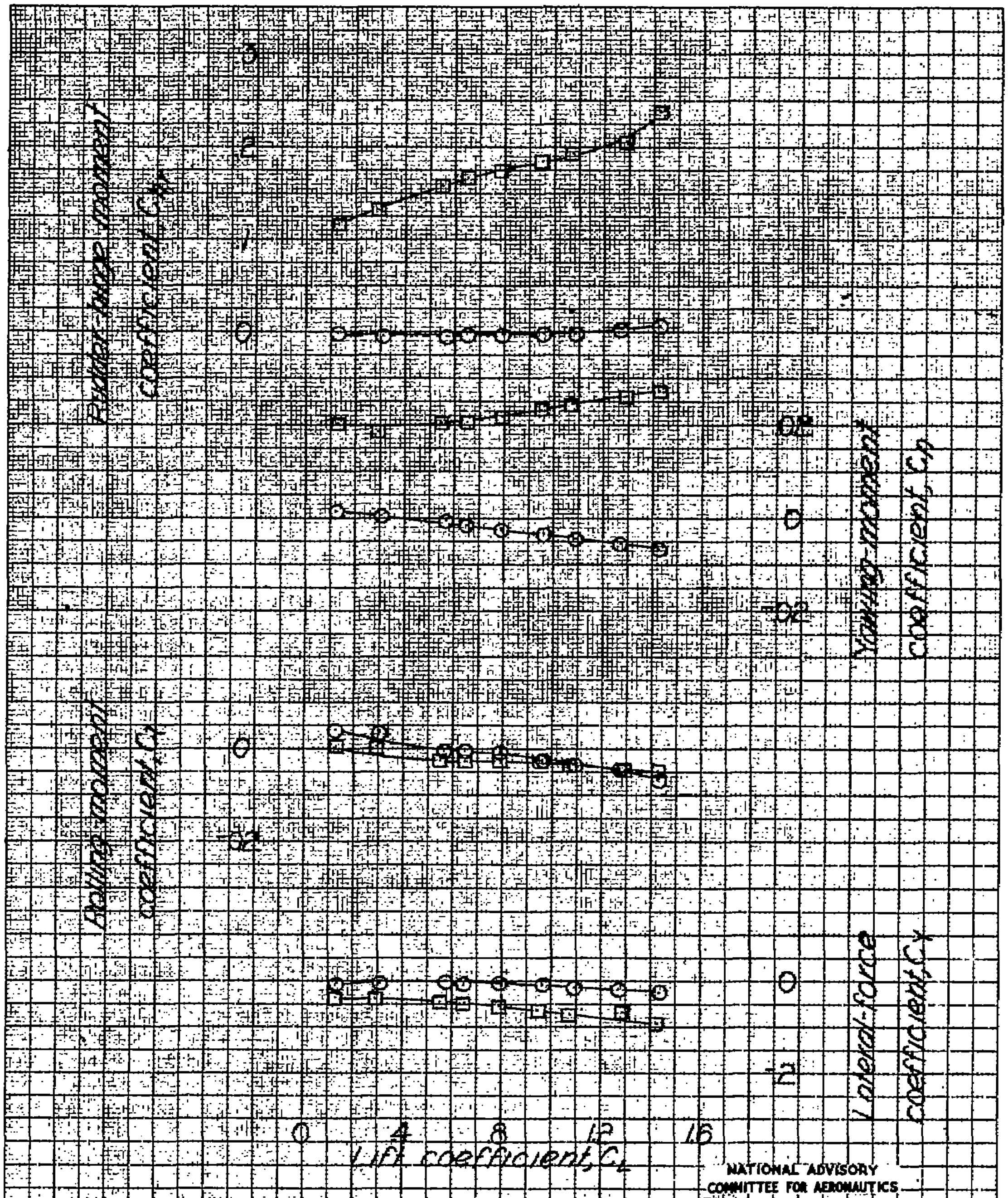
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Figure 6.- Three-view drawing of F6F-3 airplane.



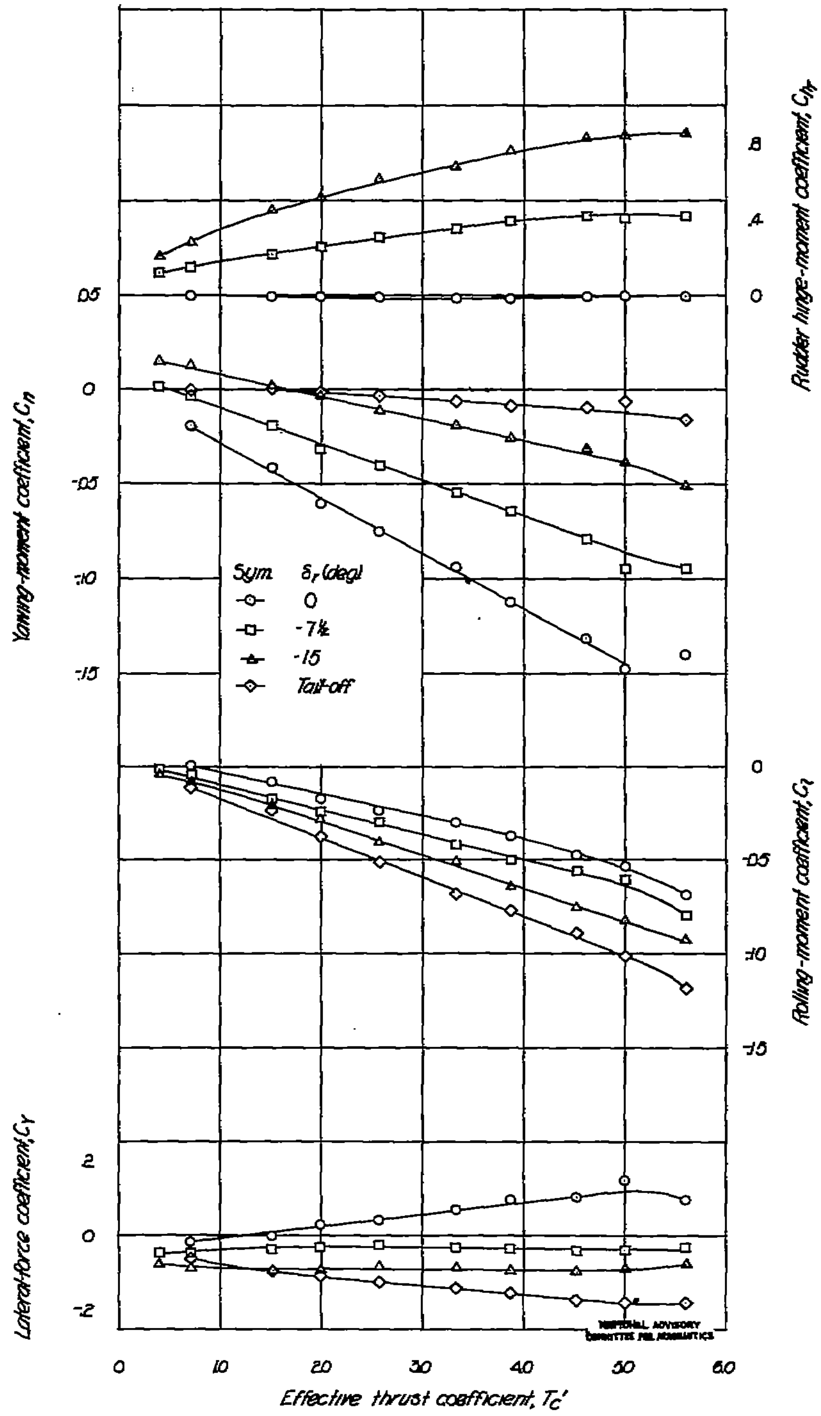
(a) Normal thrust axis.

Figure 7.- Effect of rudder deflection on the aerodynamic characteristics of a 1/5 - scale model of the XBTM-1 airplane in pitch. Cruising configuration, q = 16.37 pounds/square foot. β = 15, ψ = 0.



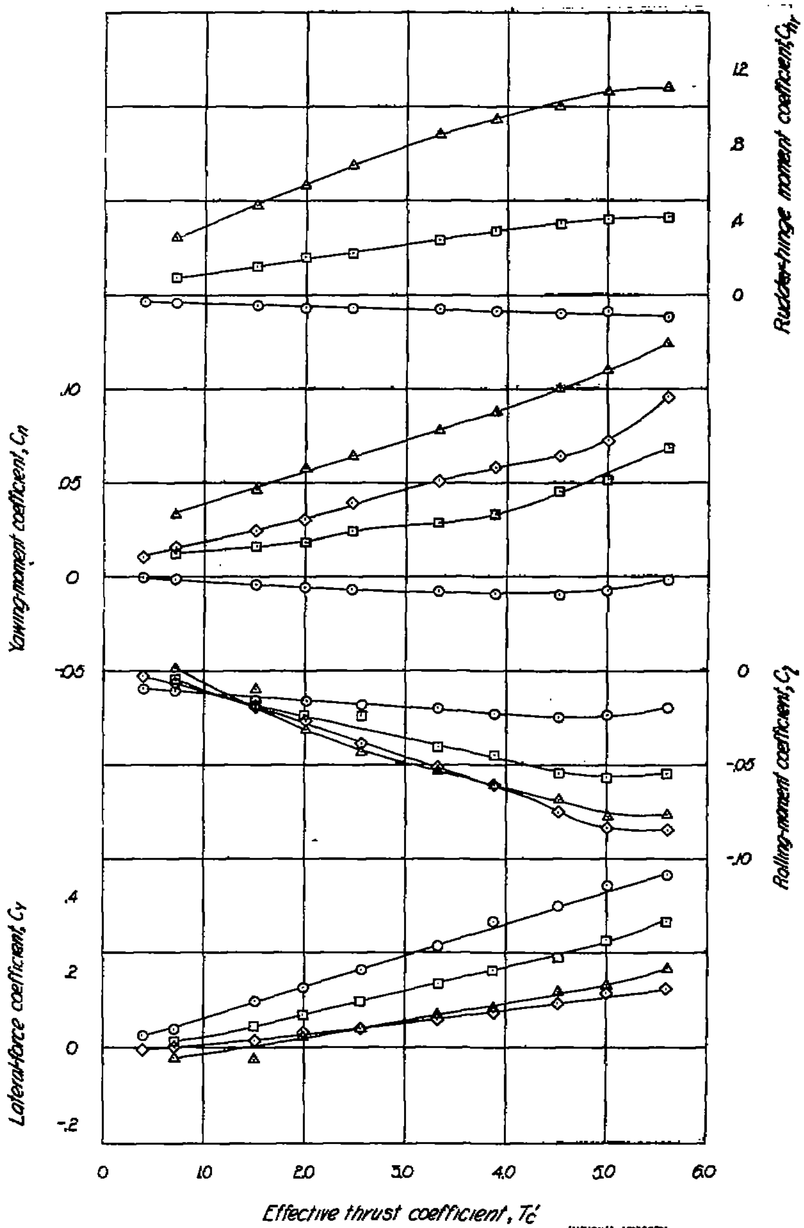
(b) Skewed thrust axis

Figure 7- Concluded



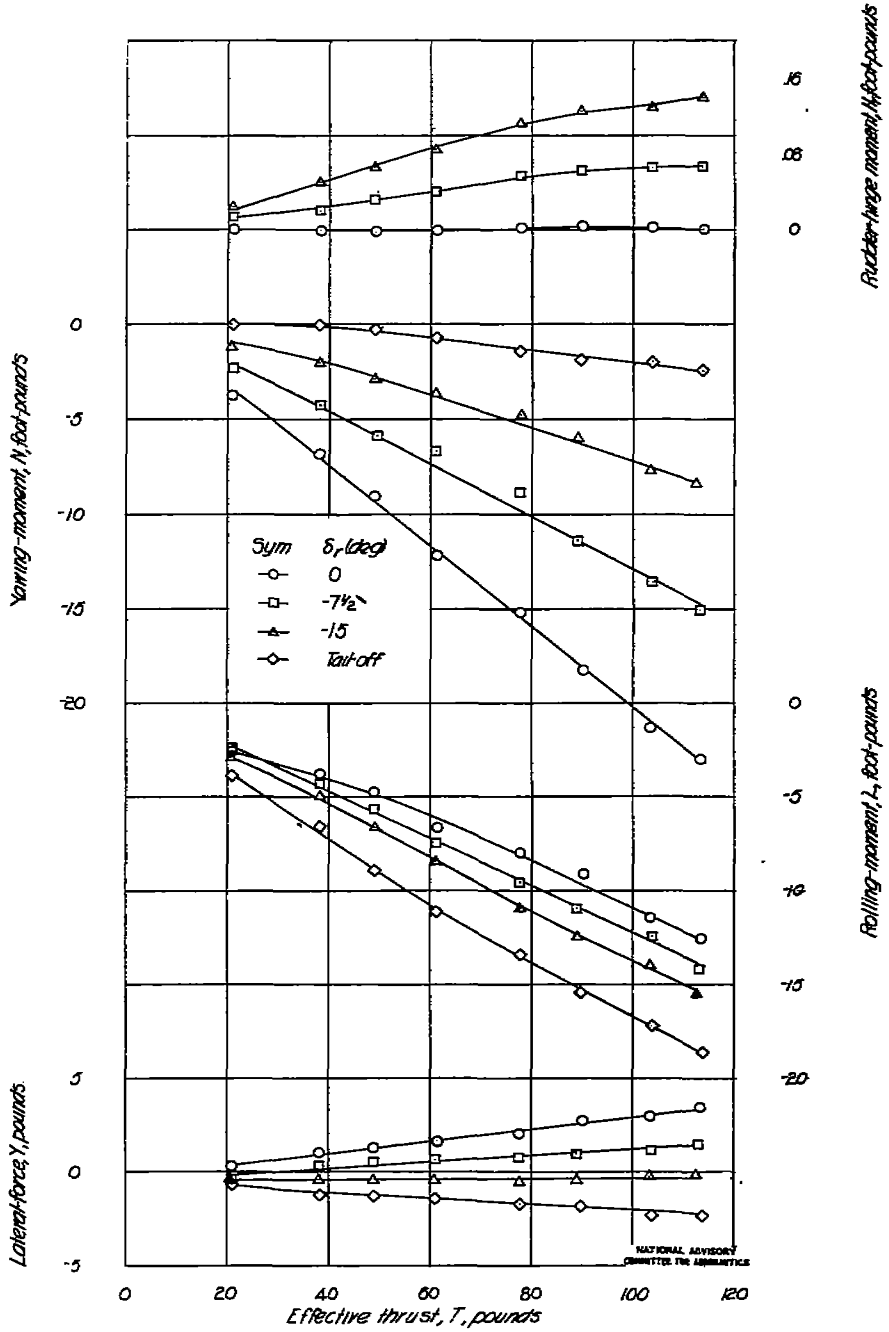
(a) Normal thrust axis.

Figure 8.- Effect of rudder deflection with varying thrust coefficients on the aerodynamic characteristics of a 1/5-scale model of the XF2M-1 airplane. Blade angle 15°, cruising configuration, $\alpha = 0°$, $\psi = 0°$, $q = 23.03$ lbs/sq ft



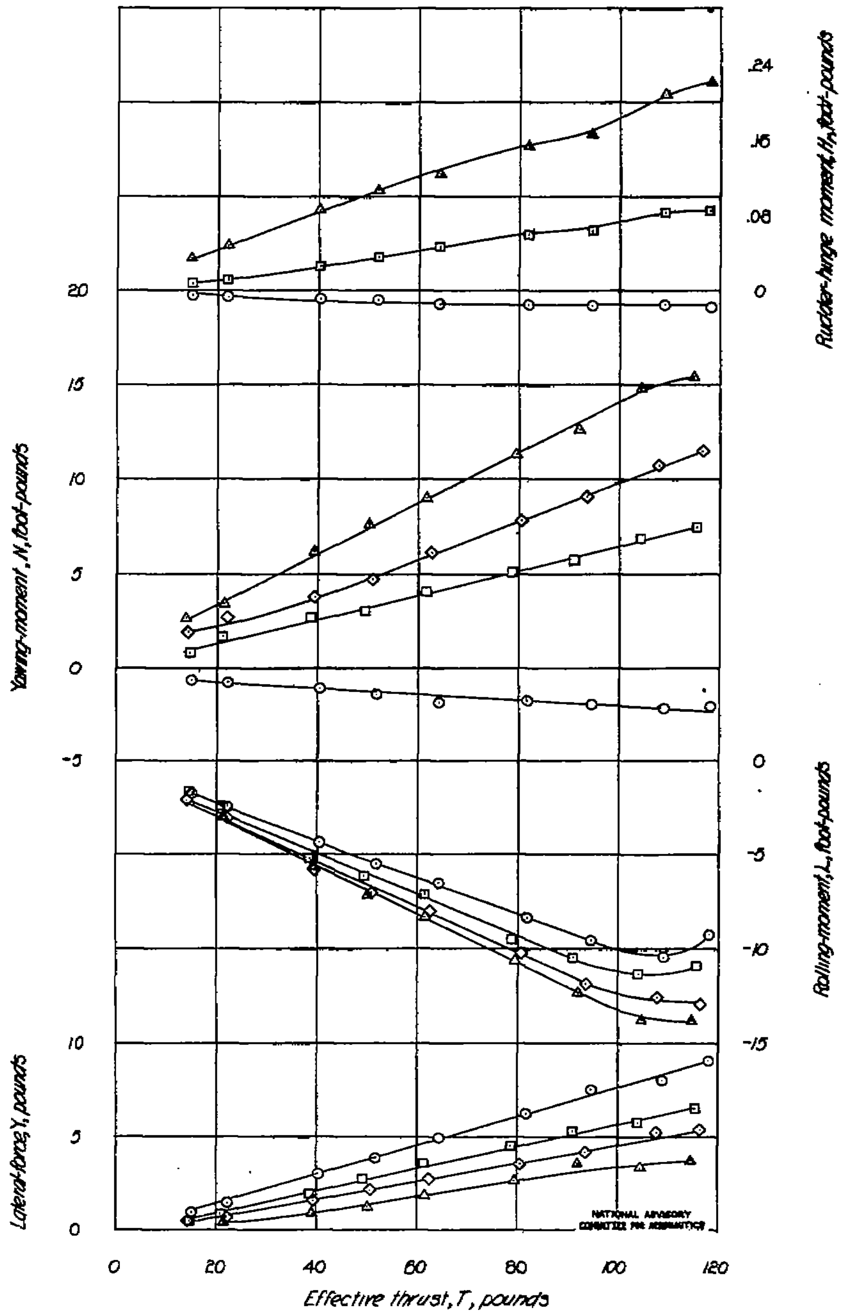
(b) Skewed thrust axis

Figure 8 - Concluded



(a) Normal thrust axis.

Figure 9-Effect of rudder deflection in the static thrust condition on the aerodynamic characteristics of a 1/5-scale model of the XF2M-1 airplane. Blade angle 15°, cruising configuration, $\alpha = 0°$, $\psi = 0°$, $q = 0$ lbs/sq ft.



(b) Skewed thrust axis

Figure 9-Concluded

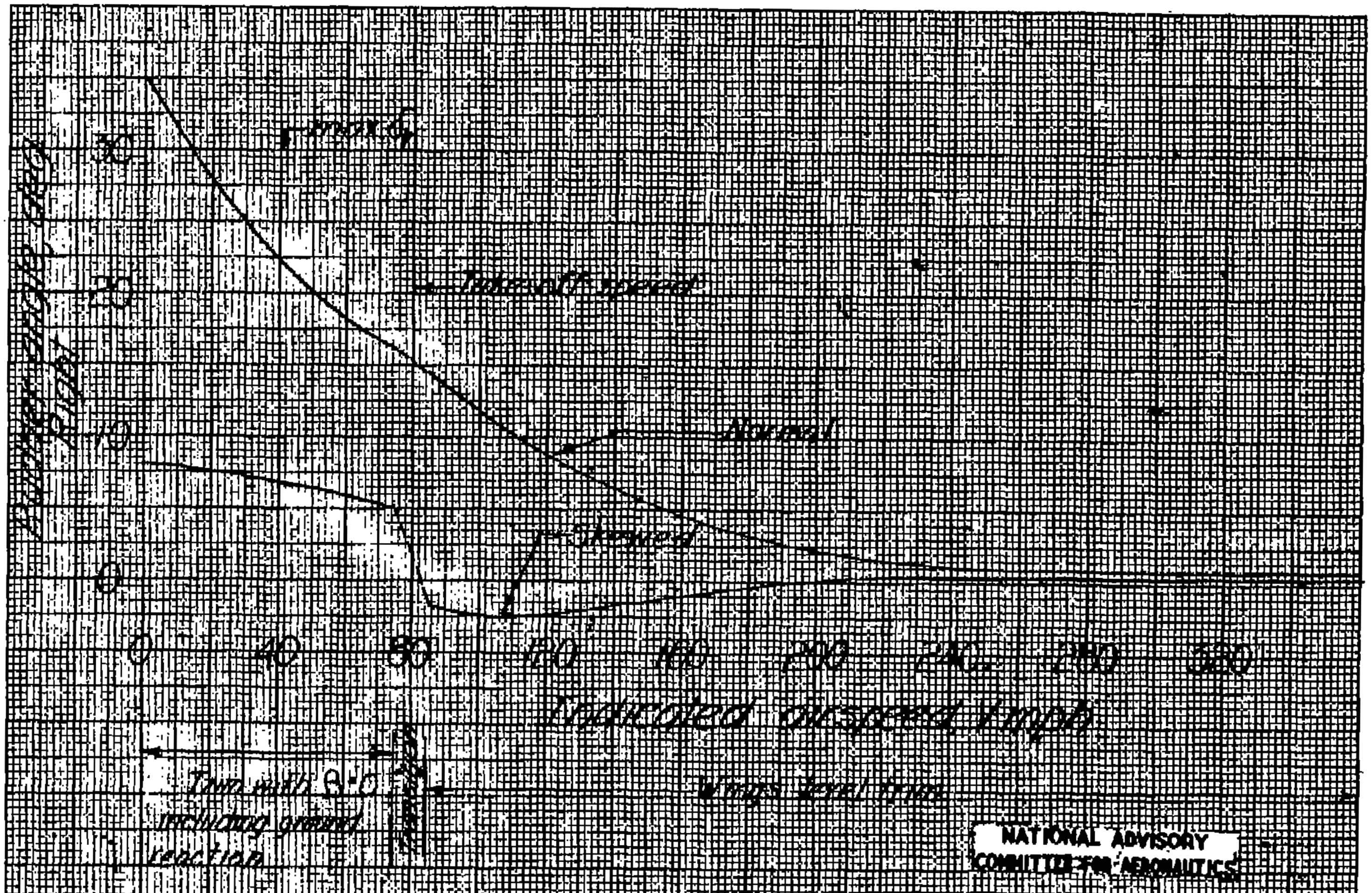
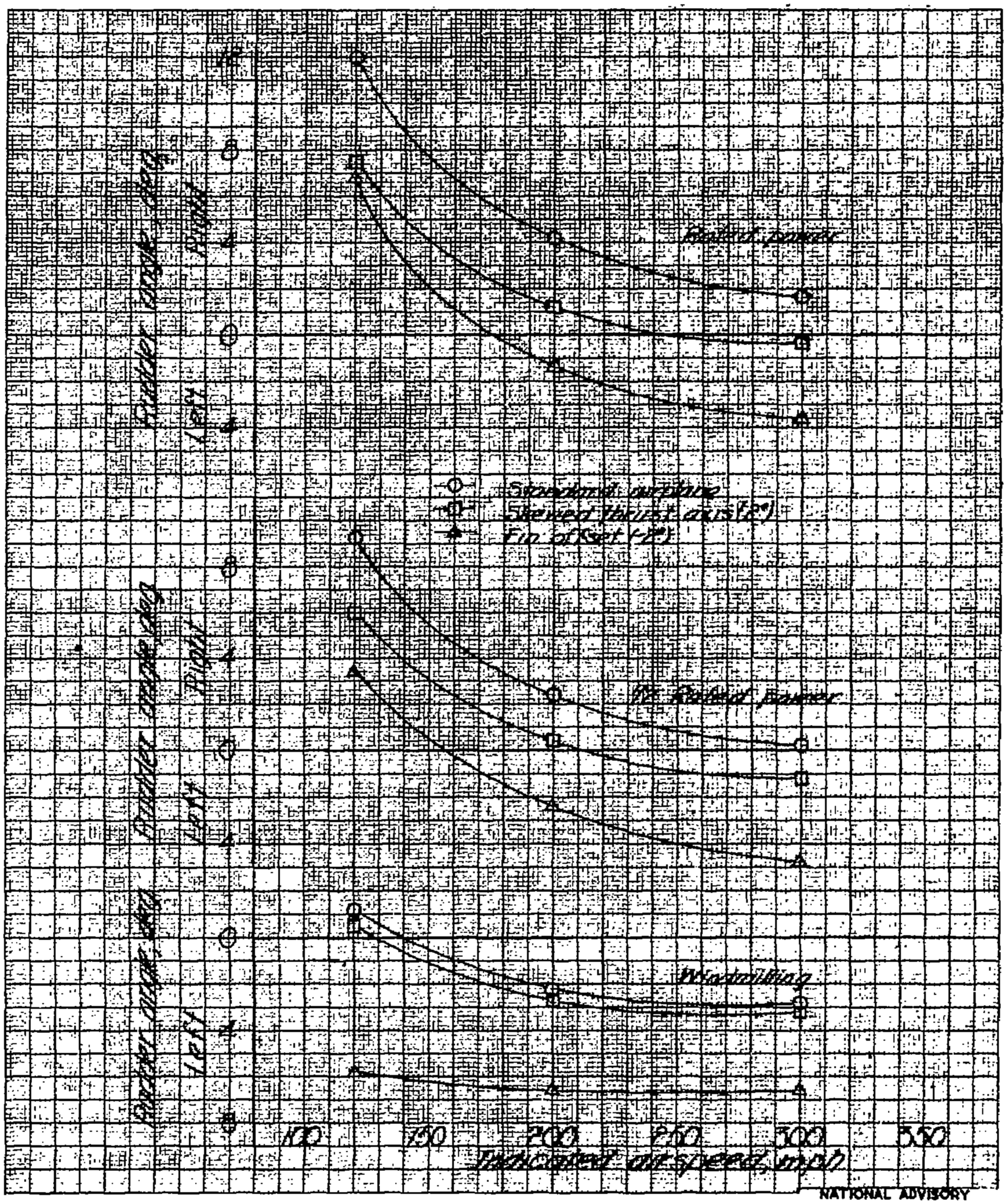


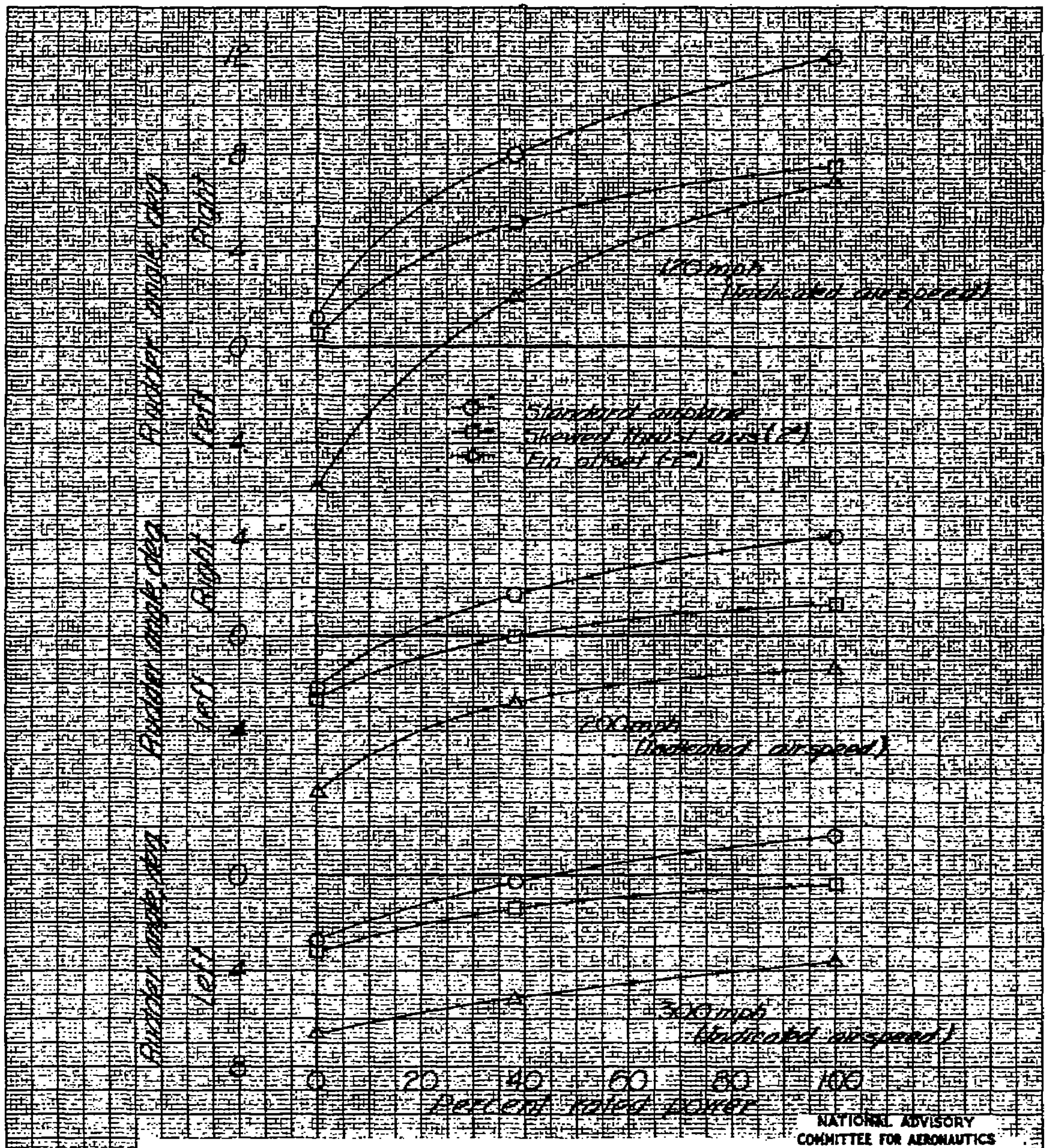
Figure 10.- Effect of skewed thrust axis on estimated rudder characteristics of the XF2M-1 airplane during ground run and climb.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

(a) Rudder angle versus indicated airspeed.

Figure 11.- Effect of skewed thrust axis and fin offset on the rudder characteristics of the F6F-3 airplane. Cruising configuration, trimmed for level flight, $F_R = 0$.



(b) Rudder angle versus percent rated power.

Figure 11.- Concluded.

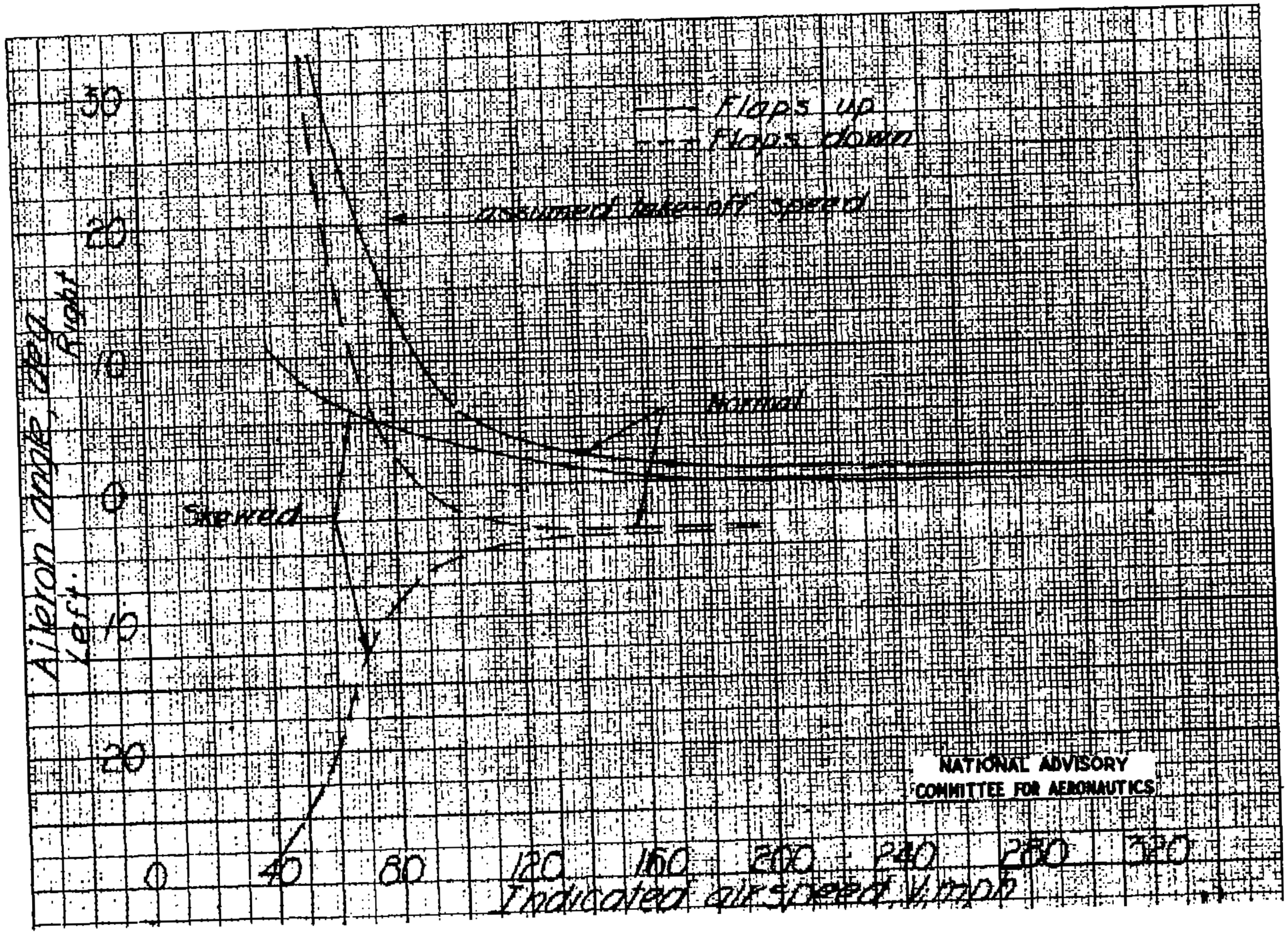


Figure 12. - Estimated aileron deflection required for wings level trim of the XF2M-1 airplane used as a single-float seaplane with normal and skewed thrust axis.

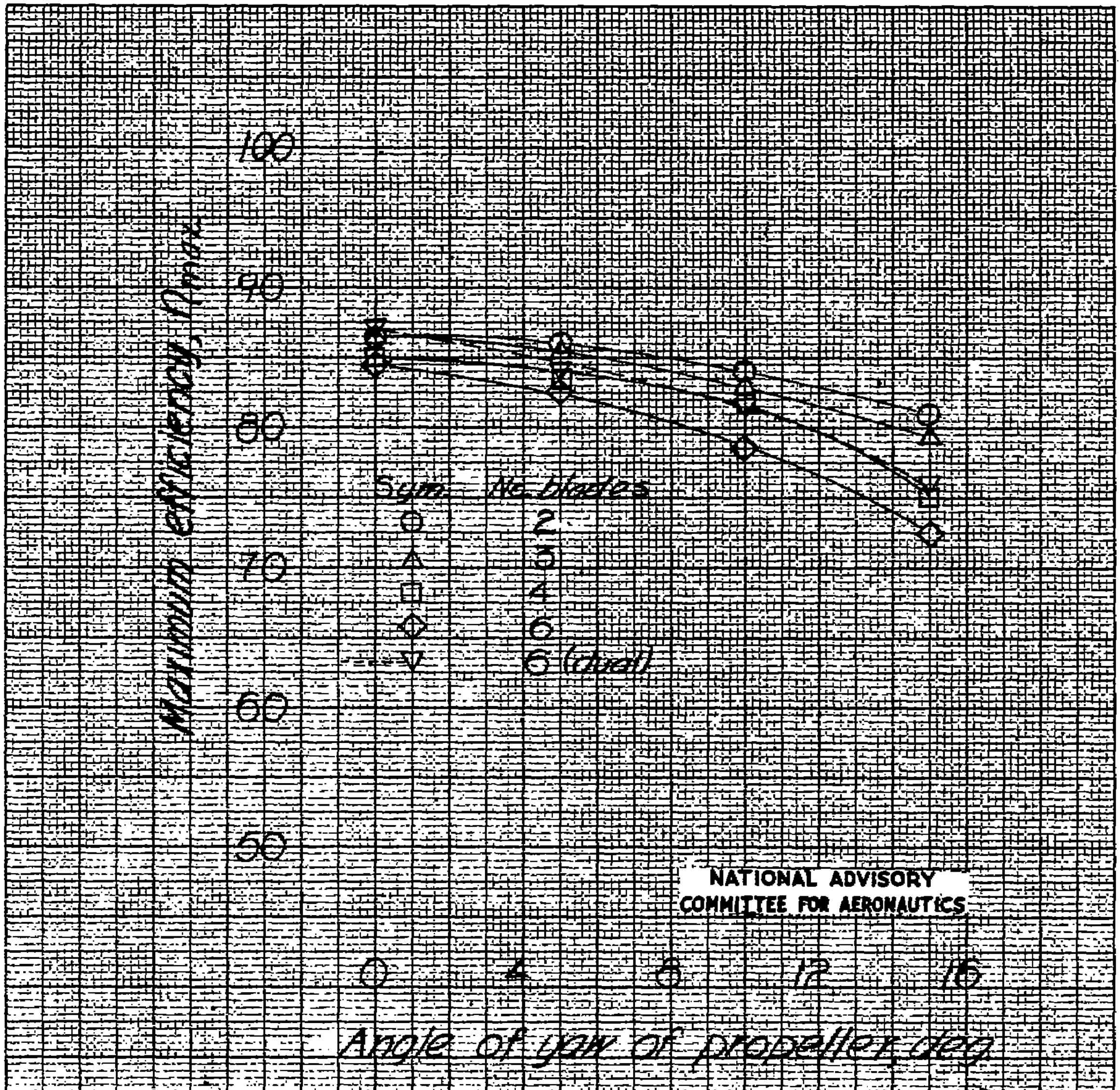


Figure 13.- Effect of yaw on propeller efficiency. Blade angle = 45° (obtained from reference 5).

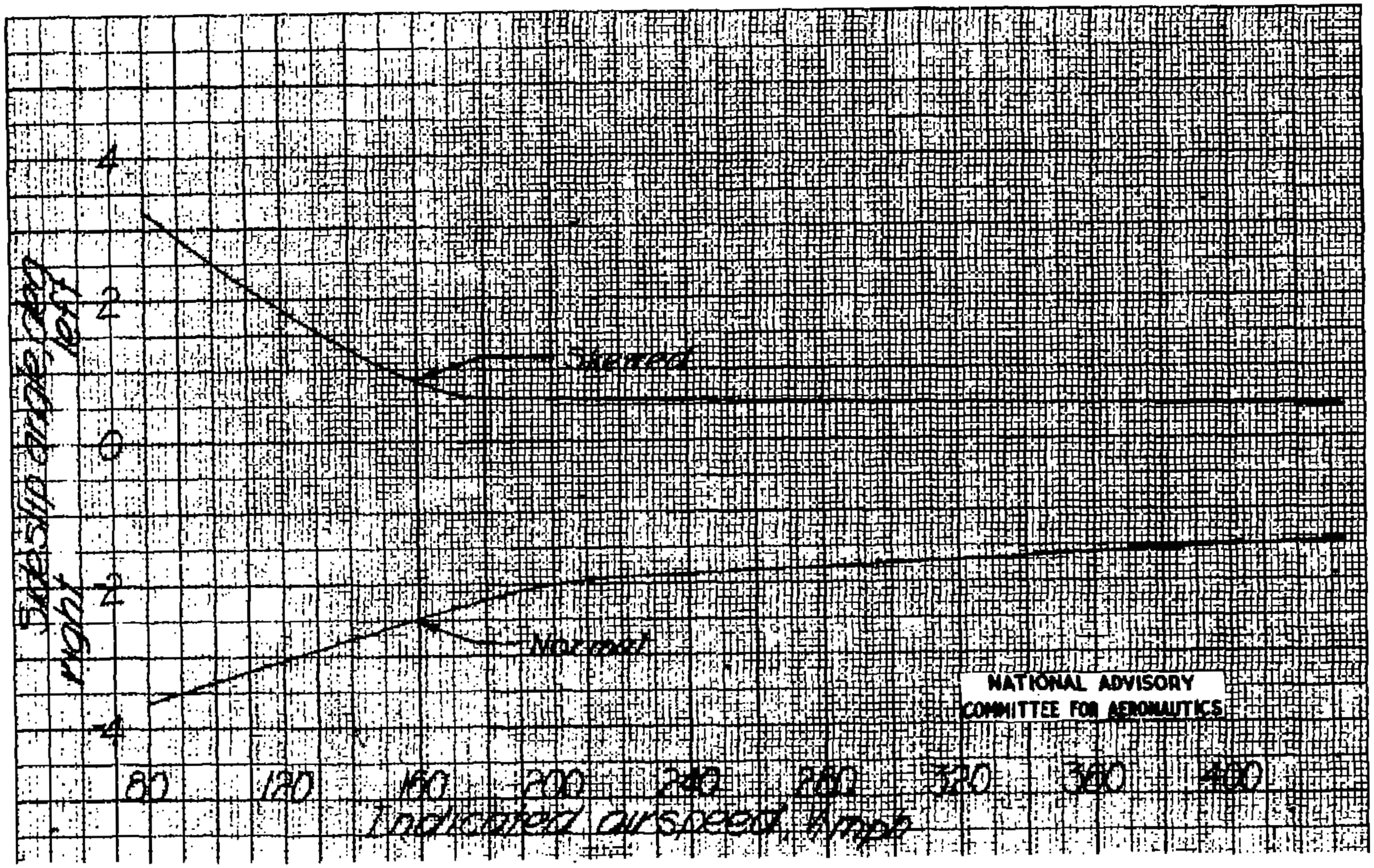


Figure 14.- Estimated sideslip angles required in straight flight for the XF2M-1 airplane. Wings level trim with the thrust axis in normal and skewed positions; cruising configuration.

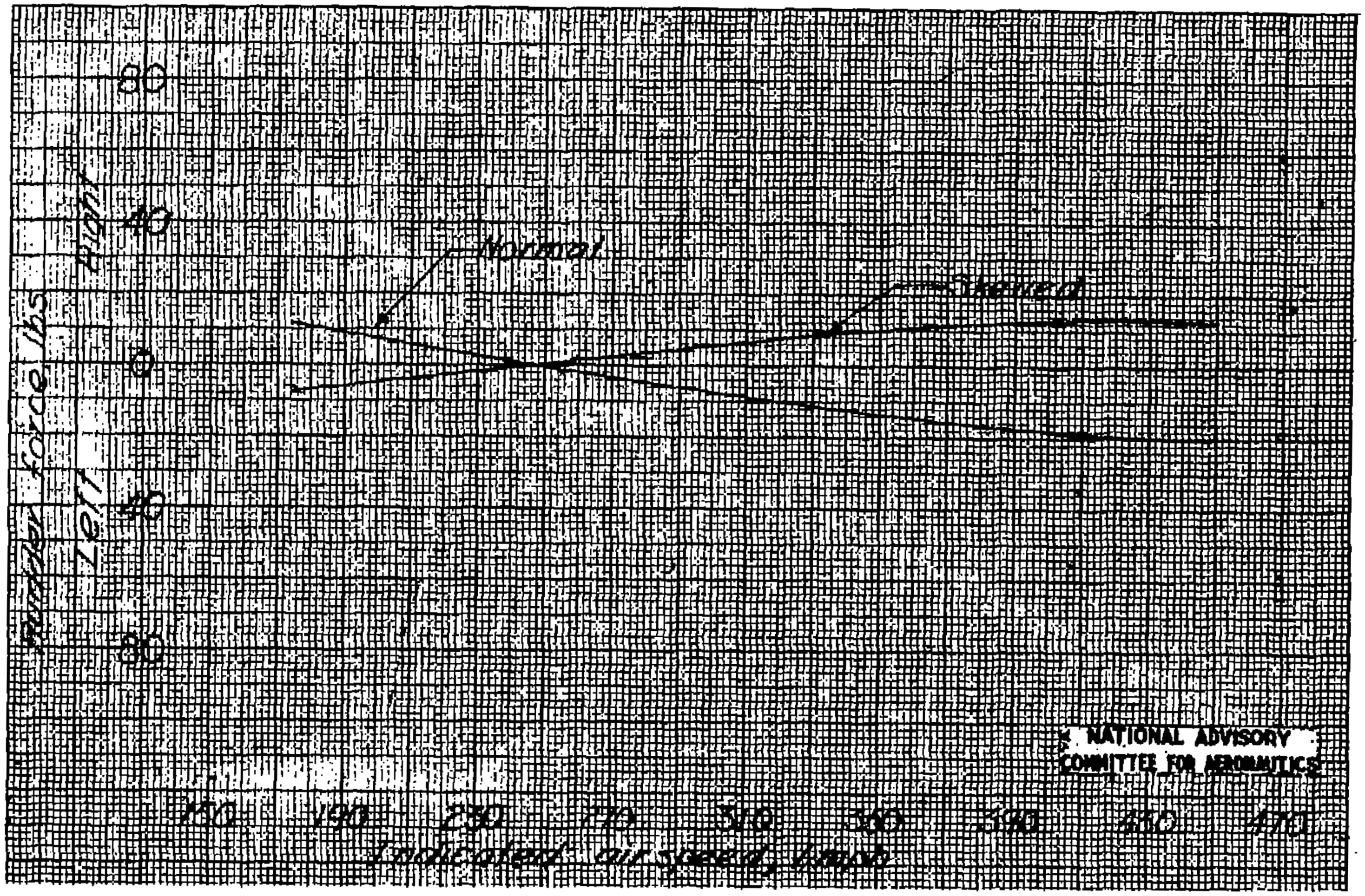


Figure 15. - Effect of skewed thrust axis on estimated characteristics of rudder required for trim in dive condition. Cruising configuration (compressibility effects excluded).